Energy Convers. Mgmt Vol. 34, No. 9-11, pp. 1213-1218, 1993
Printed in Great Britain

0196-8904/93 $6.00 + 0.00
Pergamon Press Ltd

EXERGONOMICS OF THE OCDOPUS PROJECT

E.I. Yantovskii
Institute for Energy Research, Russian Ac. Sci.
44/2 Vavilova St. 117333 Moscow, Russia.

G. Wall, L. Lindquist, J. Tryggstad
University College of Eskilstuna/Vasteras
Box 11, S-72103 Vasteras, Sweden

ABSTRACT

The project of combined production of power, carbon dioxide, process steam, hot water and compressed nitrogen for oil recovery enhancement is considered.

The exergy analysis to evaluate effectiveness of the plant is used. As the main tool the exergy flow diagrams are developed. Exergy efficiency of the plant is defined as a relation of the sum of delivered exergy flows to the exergy of consumed fuel.

At attempt to guess the invested exergy, net-exergy coefficient and the sum of specific exergy consumption (exergonomic criterion) is presented.

INTRODUCTION

In the preceding paper [1] a research-project of a zero-emission power plant for use at oil field was presented. The particular aim of the plant is carbon dioxide supply for enhancement of oil recovery along with compressed nitrogen, if necessary.

Present article is aimed at trying to evaluate effectiveness of mentioned OCDOPUS plant by means of exergy flow calculations in all the "arms". The use of exergy is unavoidable as in many multypurpose plants having released flows of different kind. Exergy efficiency η_ε can be calculated easily as a relation of delivered exergy flow to its income.

There exists, however, more advanced approach in exergy analysis, referred to as exergonomics [2]. It let us optimize the energy carriers current density and exergy efficiency itself in order to get minimum of Z-criterion, the sum of specific exergy consumption.

By no means can this approach replace economic calculations. It is useful for early scouting studies when monetary values are unknown. Here one has to use exergy values not only for current flows but also for the investment to produce equipment, especially to get materials.

The main criterion of exergonomics is as follows:

$$Z = 1/\eta_\varepsilon + 1/K_\varepsilon \quad (1)$$

where net-exergy coefficient $K_\varepsilon = \dot{\varepsilon}_{del}\tau_n/\varepsilon_{inv}$; $\dot{\varepsilon}_{del}$ - flow of delivered exergy; τ_n - life time (or normative); ε_{inv} - total amount of invested exergy.

Criterion Z has minimum in respect to exergy efficiency η_ε: $Z_{\min}=\left(1+\sqrt{-\frac{dK_\varepsilon}{d\eta_\varepsilon}}\right)/K_\varepsilon$; $\eta_\varepsilon^{opt}=K_\varepsilon/\sqrt{-\frac{dK_\varepsilon}{d\eta_\varepsilon}}$. If η_ε exeeds its opptimal value η_ε^{opt} it leads to wasteful energy use [3]. Numerical values and figures for exergy and efficiencies of industrial processes have been collected in [4], we use it here.

The main scientific question still remained in exergonomic: shall we discount exergy like money? If yes the time τ_n is much less than life time τ. We belive it is correct and assume relation $\tau_n/\tau = 0.25$.

ENHANCED OIL VERSUS CONSUMED FUEL

We do not intend to discuss the technology of oil recovery enhancement. We need to appreciate in rough figures the possibility to increase the extraction factor and relation of amount of additional oil to injected carbon dioxide.

Comprehensive review of Bondor [5] contains the figure "one barrel of incremental oil can be recovered by the use of 5 mcf of purchased carbon dioxide" which seems to be doubtful.

Some experimental results have been published in [6]. The early tests in 1967-77 have demonstrated that additional oil (28.8 th.t) was six times more than injected CO_2 (4.8 th.t). The data of increased oil extraction factor and much less optimistic relation oil/CO_2 (0.32 - 0.89) have been presented for subsequent tests on many real oil fields, see Table 1 [6].

As we mentioned in [1] the ratio oil/CO_2 = 0.5 is marginal. In case of less ratio the consumed fuel exeeds incremental oil. If an accompanying gas is used as fuel it is admissible. If crude oil is used as fuel in equal rate with the production increment the net benefit is just produced power.

Table 1.

	Oil fields				
	Sergejev	Olchov	Radaev	Kozlov	Abdrakhmanov
Permeability, mkm^2	0.23	0.04	1.54	0.24-0.28	0.548
Viscosity, mPa·s	5.7	0.72	30.7	7.0-6.1	4.0
Temperature, C	40	27	26.5	30-31	36
Pressure, MPa,	18.1	18.5	12.7	12.6	16.8
Number of wells Productive	50	76	86	50	325
Injection	16	25	27	22	93
Initial extraction, %	22.8	28.8	42.7	42.6	45.2
Water flooding, %	51.0	28.3	82.7	80.9	80.2
CO_2 in porous volume, %	15	15	12	12	30
CO_2/H_2O ratio	1:1.5	1:1	1:3.1	1:2.8	1:3
Extraction increase, %	10.4	12.4	12.8	10.4	13.0
Oil extraction per ton CO_2	0.56	0.48	0.89	0.67	0.32

OCDOPUS FLOWS

All the flows to and from for a 10 MW unit are presented on Fig.1. Note, however, that the plant can not produce all flows simultaneously. For example the compressed nitrogen production (7 kg/s, 300 bar) needs to consume all 10 MW of power.

The plant has some modes of operation: for power, for nitrogen or mixed. Liquid CO_2, process steam and hot water are inherent effluents of the unit.

As far as we know the use of oxygen for underground combustion is forbidden in some countries. OCDOPUS plant can provide oxygen supply but we did not examine this mode of operation in details.

EXERGY DIAGRAMS AND CRITERIONS

The ordinary Sankey-Grassman diagrams for exergy flows are presented on Fig.2. Exergy income is fuel. Exergy of air considered as zero. Exergy outflow in electrical power measured by the same amount of watts. Exergy of compressed nitrogen has been calculated by a simple formula for ideal gas. Minor exergy of hot water was omited.

For CO_2 the data of [4] are used. It was verified by summing up the exergy of CO_2 from dry air by 1 bar and compression up to 60 bar, by 293 K.

The two modes of operation, for power and for compressed nitrogen are presented on diagram. Related efficiencies are as follows:

$$\eta_\varepsilon^{power} = \frac{10 + 1.48 + 0.75}{29} = 0.42$$

$$\eta_\varepsilon^{N_2} = \frac{3.47 + 1.48 + 0.75}{29} = 0.20$$

The main problem of net-exergy calculations consists of mass evaluations of all the components of not existing facility. We make use quite a big statistics collected by Zaritski [7], see Fig.3. Here specific mass of heavy-duty gas turbines versus specific power per flowrate unit is presented. There exists correlation: the more is specific power the less specific mass.

In OCDOPUS project the total flowrate equals 53.8 kg/s and specific power is 10,000/53.8= = 185 kJ/kg. Having looked at Fig.3 one can see our appraizal for power plant near to upper figures: 10 kg/kW, it means 100 t for 10 MW power.

Averaged data for oxygen plants are around specific mass of 50 t/kg O_2,it gives the same mass for air separation unit 100 t because oxygen flowrate equals 2 kg/s. Therefore total mass of OCDOPUS is 200 t or 20 kg/kW.

Exergy intensity of steel, heavily stainless, is about 100 MJ/kg [4].Therefore total exergy investment is around 200.100 = 20 TJ.

Delivered exergy per normative time τ_n=8 years and 20 megasec of working time in a year equals:

$$10^6 \cdot 8.2 \cdot 10^7 = 1600\text{TJ}$$

Net-exergy coefficient K_ε is equal 1600/20=80. It is very high value of K_ε therefore the role of invested exergy in Z criterion is small as in many fuel-fired power plants. If it is approved by more rigorous calculations the optimization of OCDOPUS for maximal η_ε only will be justified.

CONCLUSION

Exergy efficiency of OCDOPUS seems to be quite high: 42% in power mode of operation and 20% in compressed nitrogen case.

Known experiments show marginal oil enhancement in respect to fuel consumption.

Exergy investment plays a minor role in exergonomic criterion, therefore optimization target might be exergy efficiency only.

REFERENCES

1. Yantovskii E.I et al. Oil enhancement Carbon Dioxide Universal Supply. IEA Carbon Dioxide Disposal Symposium Oxford, March 1993.
2. Yantovskii E.I. Non-equilibrum thermodynamics in thermal engineering. ENERGY, Vol.14, N° 7, pp.393-396, 1989.
3. Yantovskii E.I. An attempt to generalise exergy analysis referred to as exergonomics. ATHENS'91, Proc. of the Intern. Conf. June 3-6, 1991, Athens, Greg Foundas.
4. Szargut J., Morris D., Steward R. Exergy analysis of thermal, chemical and metallurgical processes. NY, Hemisphere 1988.
5. Bondor P.L. Applications of carbon dioxide in enchanced oil recovery. ENERGY CONVERSION AND MGMT, Vol.33, N° 5-8, pp.579-586, 1992.
6. Pantelejev V.G. et al. The use of carbon dioxide for enhancement of oil recovery. OIL ECONOMY N° 10, pp.17-19, 1985 (in Russian).
7. Zaritski S.P. Diagnostics of gas pumping units with gas turbine drive. Moscow, Nedra, 1987. (in Russian).

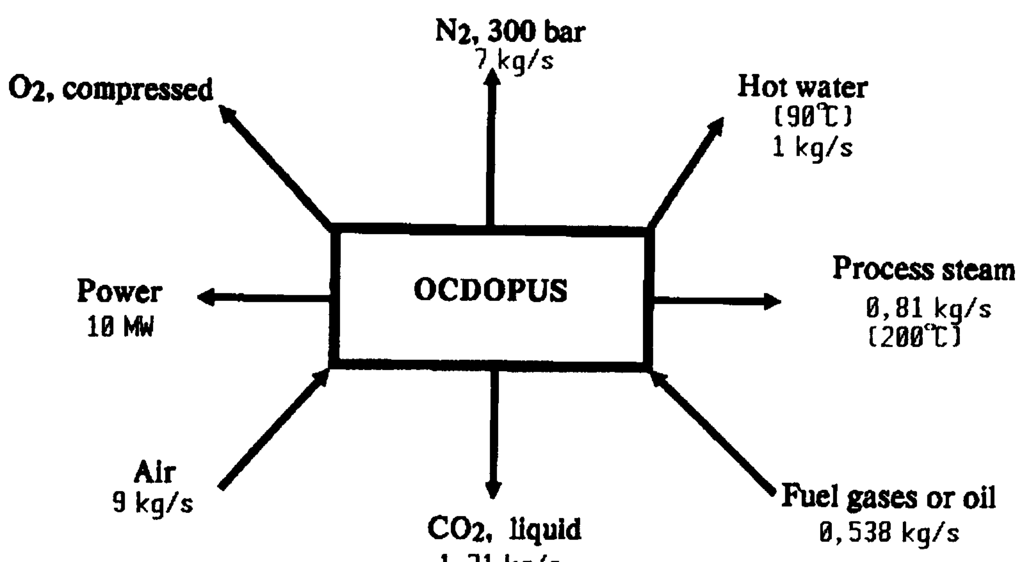

Fig.1. OCDOPUS production and consumption

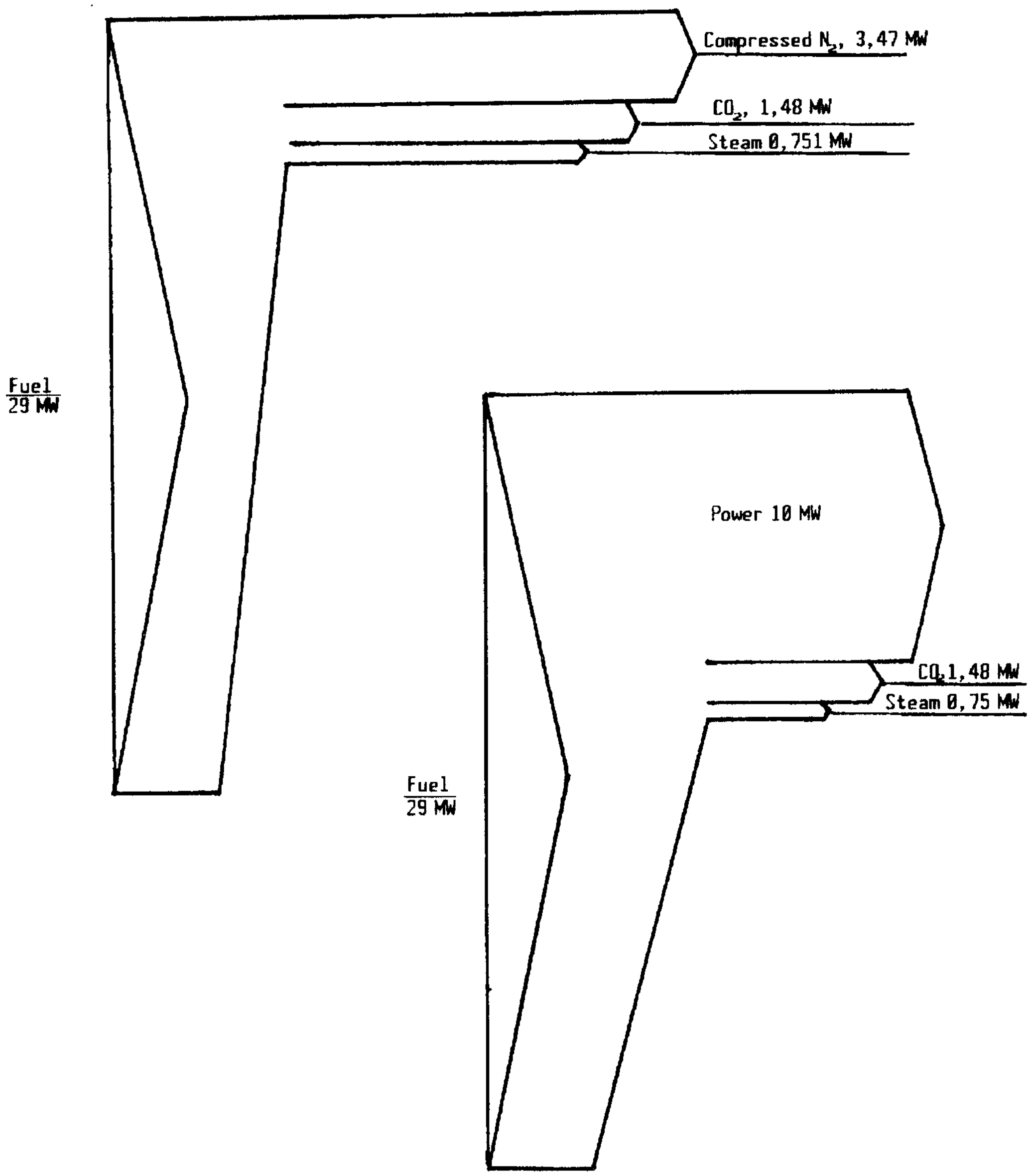

Fig.2 Exergy flow diagrams of OCDOPUS

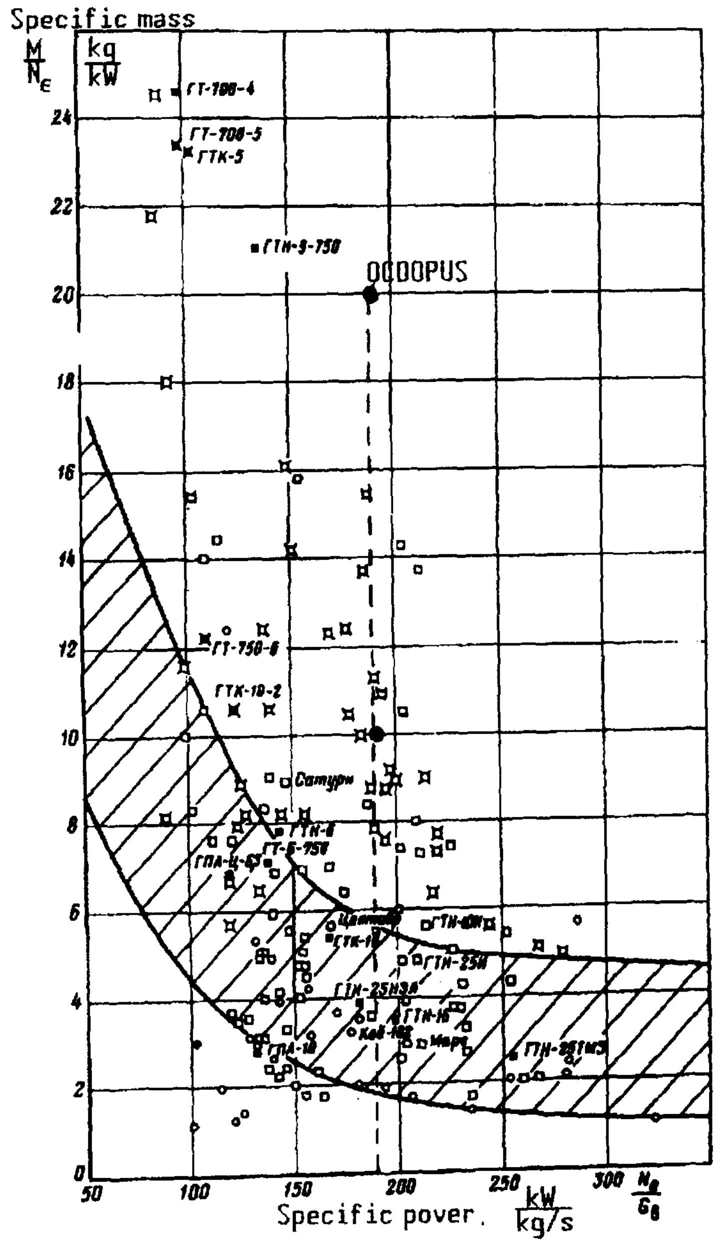

Fig.3. Heavy-dutty gas turbine statistics and OCDOPUS point